MOUNTAIN HEMLOCK (*TSUGA MERTENSIANA* [BONG.] CARR.) GROWTH AND COOL-SEASON PRECIPITATION IN CRATER LAKE NATIONAL PARK, OREGON

A Thesis
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF ARTS

Dr. Scott St. George

April 2015

Acknowledgements

I would like to thank Crater Lake National Park for their gracious support throughout my project, and Dr. Calvin Ferris for his assistance planning and preparing for field work. Thank you to the National Park Service (Cooperative Agreement #H6000082000) for providing the funding that made this research possible. I would like to express my deepest gratitude to my adviser Dr. Scott St. George whose patience I tested over the last few years. Thank you for your wisdom, advice, and much needed direction. To Dr. Kurt Kipfmueller, thank you for your assistance, advice, good humor, and for allowing me to live in the measuring room for nine months. Your help with correctly identifying anatomical anomalies and working out difficult dating issues (1810) was particularly appreciated. Finally, thank you Dr. Rebecca Montgomery for your advice on time management and writing. In addition to my committee I would like to express my gratitude first to Dr. Daniel Griffin, for your helpful discussions during the analysis and writing processes. Second, to Emily Smoter, I truly appreciate all of your hard work in the field and our great conversations both in the field and in the lab. Elizabeth Schneider, thank you for your invaluable editing expertise, the moral support, and numerous venting sessions, you get a plus on the board. Finally, I would like to thank Stephen Ferguson for all the editing you've done for me over the last few years and for your love and support throughout the entire journey.

Dedication

I dedicate my thesis to my grandmother Ada Marie Appleton. Without her generosity, encouragement, love, and support it would not have been possible. I hope that this achievement fulfills the dream she had for me.

Abstract

This study describes the development of a new network of mountain hemlock (*Tsuga mertensiana* [Bong.] Carr.) records at high-elevation sites in Crater Lake National Park (CRLA), Oregon, and uses these data to make inferences about past climate in the park during the last five and a half centuries. The seven hemlock chronologies, which are constructed from 53-80 tree-ring samples at each location, are highly synchronous over time, which suggests that tree growth across the Park is controlled by similar sets of environmental factors. The climate signal preserved in tree-ring-width series was estimated by comparing them against local monthly climate data, and that analysis showed an inverse relationship between tree growth and cool-season precipitation (previous November, previous December, January, March and April) and a more modest positive relationship with growing season temperature (April-August). The inverse association between cool-season precipitation and hemlock growth is opposite to the relationship displayed by most tree-ring records in western North America. Based on the observed association between hemlock growth and climate, I identify several periods during the past five centuries where snowpack in CRLA was persistently high or low. Tree growth was combined with observed anatomical anomalies, including locally absent rings, traumatic lenses, and light latewood, to estimate past hydroclimate conditions within the park. The sequence from A.D. 1809, 1810, and 1811 stands out over the last five centuries because of its low growth and high concentration of anatomical anomalies, which are interpreted as evidence for the early onset of winter in A.D. 1809 and an exceptionally short growing season in A.D. 1810.

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Introduction

Over the last century the central Pacific Coast of United States has experienced major shifts in wet and dry conditions. These shifts have caused periods of water stress, including the unprecedented drought in California from 2012-2014 (Griffin and Anchukaitis, 2014), as well as periods of flooding (Cayan *et al.*, 1998) that greatly affected local communities. In this region, a majority of the local precipitation falls during the winter as snow (Cayan *et al.*, 1998; Pederson *et al.*, 2011). Snow is an important part of the hydoclimate and hydrology of this region, particularly its contribution to the Klamath River, which is a key resource for southern Oregon and northern California (Levy, 2003; Malevich *et al.*, 2013). Meteorological data from this region only provides a short-term perspective of climate variability (A.D. 1893 to 2012; Quinlan *et al.*, 1987) and cannot encompass a full spectrum of events and long-term climate patterns. In order to explore local climate beyond the local instrumental record, we must use proxy records.

Proxy records that incorporate information about climate, such as tree-rings, can help extend knowledge about extreme events and long-term patterns back centuries. Trees in temperate and boreal forests form annual growth rings, and through the process of crossdating, the patterns in ring-width can be compared among samples to determine the precise calendar year associated with each ring (Douglass, 1941). There are many biotic and abiotic factors that impact tree growth and cause differences in ring sizes between individual trees and among years (Cook, 1987; Briffa *et al.*, 1996). These differences in growth patterns can be influenced by climate in regions where those variables limit resources necessary for tree growth (Fritts, 1971, 1976; Vaganov *et al.*, 2010).

While there are several climate-related factors that affect tree growth, St. George (2014) reported the most common climate response exhibited by ring-width records across the Northern Hemisphere within the International Tree Ring Databank have a positive association with winter precipitation, where high rain or snow during the cool season leads to enhanced tree growth. However, a select few species such as subalpine fir (*Abies lasiocarpa* [Hooker] Nuttall) and mountain hemlock (*Tusga mertensiana* [Bong.] Carr.) show the opposite relationship, where high winter precipitation is associated with low tree growth (Graumlich and Brubaker, 1986; Peterson *et al.*, 1999; Peterson and Peterson, 2001). Previous work in CRLA has shown that mountain hemlock trees in this location are most sensitive to climate at high elevations (Peterson *et al.*, 1999) and have a negative relationship with winter precipitation and a more modest positive relationship with summer temperature (Graumlich and Brubaker, 1986; Peterson *et al.*, 1999; Peterson and Peterson, 2001). Two existing hemlock records by Briffa *et al.* (1992) and Peterson *et al.* (1999) span A.D. 1564-1983 and A.D. 1576-1992, respectively, and were used in a temperature reconstruction of western North America and a reconstruction of the water level of Crater Lake. However, neither of these hemlock records cover the most recent two decades (A.D. 1992-2012), and during that period spring snowpack in the northern Cascade Mountains has declined by more than 20 percent (Stoelinga *et al.,* (2010). Further, Peterson *et al.* (1999) reconstructed lake level with 25 trees from their seven sites. Reconstructing climate from chronologies with a small number of samples runs the risk that the resulting product includes the influence of non-climatic factors. Additionally, in their study, they sampled two transects at three different elevations, one on the east slope of the caldera and one on the west side and determined that the highest elevation sites were most sensitive to climate (Peterson *et al.*, 1999). Their reconstruction, however, included only two high-elevation records, which could have led to biased results due to local factors such as stand dynamics or microclimate. The mountain hemlock record from the Briffa *et al.* (1992) reconstruction consists of tree-ring width data from 27 cores, which is still not sufficient to reliably analyze local paleoclimate.

In this study I describe the development of a new network of mountain hemlock records at high-elevation sites in Crater Lake National Park (CRLA), Oregon, and use these data to make inferences about past climate in the park during the last five centuries. I estimate the climate signal preserved in mountain hemlock tree-ring-width series by comparing them against local monthly climate data. I also create annual records of anomalous tree growth and use these observations to identify exceptional environmental conditions within the park prior to the twentieth century. Finally, I compare my data against other proxies from the region, estimate past changes in CRLA's climate, and describe tree-ring evidence for the exceptional sequence of weather events in A.D. 1809 and 1810.

The Southern Cascade Mountains

Geology and Physiography of the Southern Cascades: The Cascade Mountain Range extends more than 1,100 km from southern British Columbia to northern California. The range formed approximately 40 million years ago when the Juan de Fuca plate collided with the North American plate, forming a subduction zone (Winter, 2010). The area remains actively volcanic and is part of the Pacific Ring of Fire. The Cascade Mountains contain a variety of elevation-dependent ecosystems, the highest of which is alpine tundra above 2,200 m. Between 1,900 m and 2,200 m there exist parkland meadows and tree islands. Below that are the high altitude forests, composed predominantly of mountain hemlock and pacific silver fir (*A. amabilis* Dougl. Ex Forbes). Other species also play a significant role in the environment such as subalpine fir, noble fir (*A. procera* Rehd.), red fir (*A. magnifica* A. Murr.), Engelmann spruce (*Picea englemannii* Parry ex Engelm.), lodgepole pine (*Pinus contorta* Douglas ex. Loud.), whitebark pine (*P. albicaulus* Englem.), and Alaskan cedar (*Chamaecyparis nootkatensis* (D. Don) Spach) (Sea and Whitlock, 1995; Grigg and Whitlock, 1998).

For the purposes of this study, the Southern Cascade Mountains is defined as the portion of the Cascade Mountains 150 km from the southern border of the state of Oregon and includes two ecoregions: the High Southern Cascade Montane Forest and the Southern Cascade, which is a discontinuous region located in southern Oregon and northern California (Thorson *et al.*, 2003). The High Southern Cascade ecoregion is a series of high elevation landforms between 1,200 m and 2,400 m that support coniferous forests composed predominantly of mountain hemlock. Other species present include

Pacific silver fir, grand fir (*A. grandis* [Dougl. ex D. Don] Lindl.), white fir (*A. concolor* [Gord. and Glend.] Lindl. ex Hildebr), and Shasta red fir (Thorson *et al.*, 2003).

Modern Climate of the Southern Cascades: The climate of the southern Cascade Mountains is marked by cool, wet winters and warm, dry summers (Sugihara *et al.*, 2006; Skinner and Taylor 2006). Winter precipitation is the largest fraction of annual precipitation in this region and has a significant impact on local water supply (Cayan *et al.*, 1998; Pederson *et al.*, 2011; National Resources Conservation Service, 2013). Prolonged periods of reduced snowpack could stress water infrastructures that rely on seasonal recharge by snowmelt (Pederson *et al.*, 2011).

El Niño Southern Oscillation (ENSO), an interannual oscillation in sea surface temperature (SST), sea level pressure (SLP), and wind in the central Pacific Ocean, and the Pacific Decadal Oscillation (PDO), an interdecadal fluctuation of sea surface temperatures in the North Pacific Ocean, are two major players in the global climate theater (Mantua *et al.*, 1997). Both regimes have two phases and extensive teleconnections across the globe. Both PDO and ENSO events have a particularly strong impact on the Pacific Coast of the United States. The climate of the central Pacific Coast, however, shows little correlation with either ENSO or PDO, despite its proximity to the North American teleconnection centers for both regimes (Florsheim and Dettinger, 2007; Ault and St. George, 2010).

Crater Lake National Park

Geology and Physiography of Crater Lake National Park: Crater Lake National Park was established in A.D. 1902 to protect the natural beauty of the United States' deepest lake and its surrounding ecosystems, and consists of 645 km^2 of protected land located in the Cascade Mountain Range in the state of Oregon (Figure 1; National Park Service, 2013a & 2013b). Crater Lake formed with the collapse of Mount Mazama approximately 7,700 years ago, which created a caldera eight km across and 1,600 m deep that was followed by an influx of ground water establishing a 592 m-deep lake. The area continues to be volcanically active (United States Geological Survey, 2005).

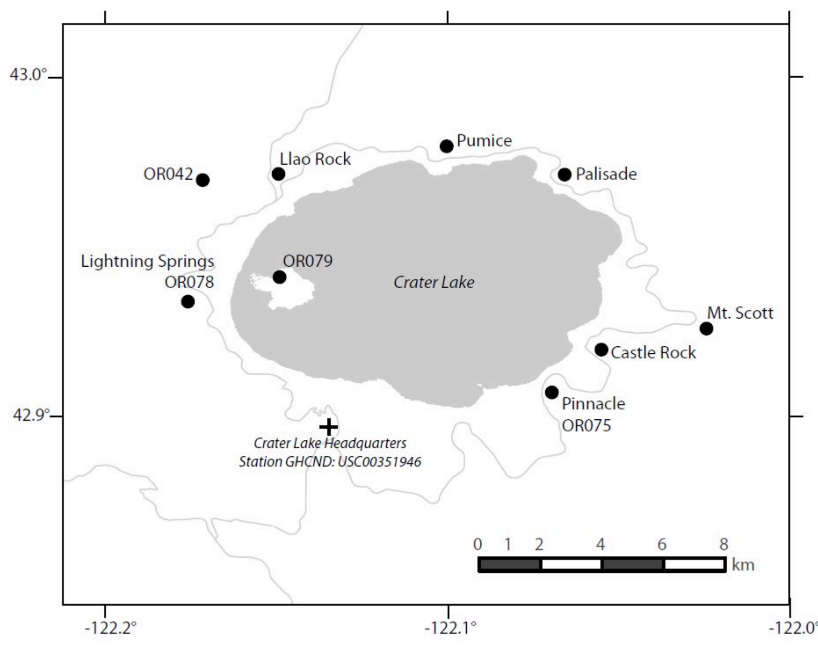


Figure 1: Map showing the location of mountain hemlock (*Tsuga mertensiana* [Bong.] Carr.) tree-ring width records developed in this study. Records with site identification codes from the International Tree-Ring Databank (e.g. OR078) were collected by Peterson *et al.* (1999) and Briffa *et al.* (1992).

Vegetation of Crater Lake National Park: Because Crater Lake National Park was established before wide-scale logging reached the region, the park includes several old growth forests (National Park Service, 2001). Tree species in the park are adapted to three key traits: a short growing season, volcanic soils, and high amounts of snowfall. Four distinct forest zones are present within CRLA, and are separated by elevation; the ponderosa pine (*P. ponderosa* Douglas ex. C. Lawson) zone (1,379 m), lodgepole pine forests (1,520 m), the mountain hemlock zone (1,830 m), and the whitebark pine zone (2,290 m). Mountain hemlock is the dominant species of the mountain hemlock zone (National Park Service, 2001).

Modern Climate of Crater Lake National Park: Overall, the climate of CRLA can be summarized as cool and wet during the winter and warm and dry in the summer months. The park receives approximately 1,627 mm of precipitation annually, and due to its location in the High Cascades approximately 70% of that falls as snow between November and March (Jackson and Faller, 1973; Murray and Rasmussen, 2003; Figure 2). Average annual temperature of the instrumental climate data is 2.8°C (Figure 2). Annual temperatures were above average for five consecutive years or more from A.D. 1939 to 1943 and 2000 to 2005. Likewise, three occurrences of five successive years or more of below average temperatures can be seen in the series including A.D. 1893-1899, 1952-1957, and 1968-1975. The warmest year on record was A.D. 1992 with an average annual temperature of 4.5°C, while the coolest year was A.D. 1955 with an average annual temperature of 1.4°C. Several periods (A.D. 1999-2005, 1920-1925, and 1913-

1917) include five continuous years (or more) of below average precipitation. A single wet span of six years occurred between A.D. 1970 and 1975. The driest year was A.D. 1929, when the park received 838 mm of precipitation, while the wettest year on record is A.D. 1950 (2,744 mm).

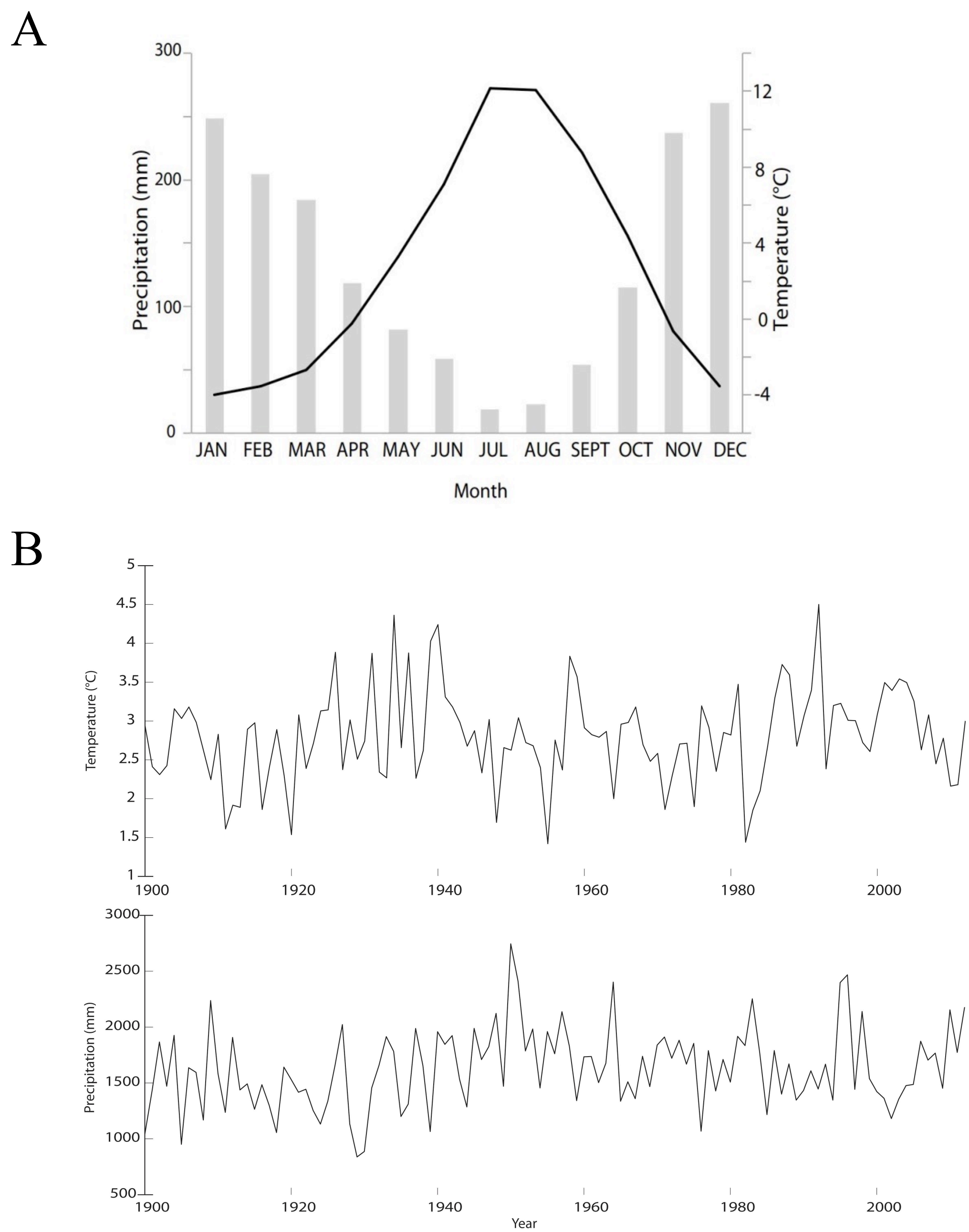


Figure 2: (A) Climograph from Crater Lake National Park (Station GHCND: USC00351946). Gray bars represent total monthly precipitation (mm) and the black line represents mean monthly temperature (°C). (B) Time series of mean annual temperature and total annual precipitation. Data were obtained from the United States Historical Climate Network climate station in Crater Lake National Park, and span the period from A.D. 1893 to 2012 (Quinlan *et al.*, 1987).

Mountain Hemlock: Mountain hemlock is a native North American conifer whose range extends from south-central Alaska to northern California (Means, 1990; United States Geological Survey, 2013; United States Department of Agriculture, 2013). Mountain hemlock trees growing in open environments have tapered trunks with slender branches that reach the ground and a conical crown with a slender drooping leader. This species can be found between 1,600 m and 2,300 m above sea level in southern Oregon (Means, 1990; United States Department of Agriculture, 2013). At low elevations (below 1,219 m) mountain hemlock grows in dense stands but on high exposed ridges the species becomes a low-spreading shrub (United States Department of Agriculture, 2013).

Mountain hemlock may be identified by its blunt-tipped needles, which are approximately 20 to 30 mm long and arranged on all sides of the branches, and a dark blue-green color with faint white lines or dots on each needle (Means, 1990; Natural Resources Canada, 2011; United States Department of Agriculture, 2013). Mountain hemlock cones are purple-brown in color, cylindrical in shape, approximately 30 to 80 mm in length, and have fan-shaped, thick plates that open in the fall (Natural Resources Canada, 2011). Finally, this species has a tapered curved crown and a shallow, widespread root system that makes it vulnerable to wind throw, when trees are uprooted or damaged by wind (Natural Resources Canada, 2011; United States Department of Agriculture, 2013).

Mountain hemlock grows in wet subalpine climates with short growing seasons. This tree species requires early snowfall to cover the soil to prevent it from freezing and depends on a deep snowpack to protect it from spring frosts (Krajina and Brook, 1970).

This species requires five main winter conditions for optimal growth: (1) 40 to 120 frost-free days, (2) a mild mean monthly temperature during the month of January between -9°C and -1°C, (3) one to six months with an average below zero degrees Celsius, (4) an absolute temperature above -35°C to -23°C, and (5) annual snowfall amounting to between 280 and 2,032 cm (Krajina and Brook, 1970).

Mountain hemlock is susceptible to a variety of insects and diseases. Laminated root rot (*Phellinus weiri*) (Means, 1990), a fungus that spreads along the tree roots to neighboring trees, is the most common malady but others include a variety of heart rots (*Heterobasidion annosum*, *Phellinus pini*, *Formitopsis pinicola*, and *Phaeolus schweinitzii*), needle infections (*Herpotrichia nigra*) (Means, 1990), snow mold (United States Department of Agriculture, 2013), and dwarf-mistletoe (*Arceuthobium tsugense*) (Means, 1990). The most common insect that infests this species is the western spruce budworm (*Choristoneura occidentalis* Freeman). Mountain hemlock is also fire intolerant but can withstand frost conditions (United States Department of Agriculture, 2013).

Previous Tree-Ring Work: Tree-ring research on mountain hemlock shows that, throughout its range, the radial growth of this species is limited primarily by two climate variables, temperature and precipitation. In Alaska, the northern portion of mountain hemlocks range, the species is mainly sensitive to summer temperature, while in California (Gedalof and Smith, 2001) the species is predominately limited by winter precipitation, but also has a strong relationship with growing season temperature

(Graumlich and Brubanker, 1986; Peterson *et al.*, 1999; Peterson and Peterson, 2001; Hart *et al.*, 2010).

Two dendroclimatic studies in CRLA or including sites within the park have used mountain hemlock. Briffa *et al.* (1992) developed a mountain hemlock tree-ring record in CRLA that was included in a large regional tree-ring network used to reconstruct past temperature across western North America. The resulting reconstruction highlighted several significant warm and cool periods over the study area with an extreme cool year noted in A.D. 1601 and a cold decade beginning in A.D. 1810 (Briffa *et al.*, 1992). Peterson *et al.* (1999) reconstructed the water level of Crater Lake based on the sensitivity of mountain hemlock to winter precipitation. Peterson *et al.* (1999) sampled mountain hemlock along two transects, one east and another west on the caldera rim, as well as a site on Wizard Island, at three elevations (high, medium, and low) and compared ring-widths to park climate data. Mountain hemlock in the park exhibited an inverse relationship with winter precipitation with the strongest climate signal found at higher elevations (Peterson *et al.*, 1999).

Methods

Sampling: In July and August 2013, I collected samples to develop new tree-ring records and update existing collections from mountain hemlock in CRLA. Sampling locations were selected based on the following criteria: old growth mountain hemlock trees (> 250 years old), found on well-drained soil on moderately steep slopes of varying aspects, open canopy forest or scattered trees, and trees growing at a high elevation (Fritts, 1976;

Cook and Kairiukstis, 1990). Sites were sampled on all sides of the caldera rim and were composed of mountain hemlock and mixed species forests, including lodgepole pine, whitebark pine, and red fir.

The seven sites are Lightning Springs, Llao Rock, Pumice, Palisade, Mount Scott, Castle Rock, and Pinnacle (Figures 1 & 3; Table 1). At Lightning Springs, tree-ring samples were collected at two locations on the west side of the caldera, with one stand located on a ridge top, and the other set of trees growing within a lower elevation depression. In both locations, the forest was dominated by mountain hemlock with red fir saplings present. The Llao Rock site, located on a series of steeply sloping ridges on the north side of the caldera rim, composed of closely grouped forest patches were dominated by mature mountain hemlock with a few small whitebark pine trees present. Another site was located on the steeply sloping face of Mount Scott, the highest point in the park. The forest at this site is dominated by mountain hemlock with some whitebark pine also present. The forest floor was very rocky and had woody debris from tree fall. The Pumice site, located on the north side of the rim, was a gently sloping, park-like, mature mountain hemlock stand. The Palisade site, located on the steep slope of the northeast portion of the caldera, was a mixed species stand of mountain hemlock, red fir, and whitebark pine. The Castle Rock site refers to a series of meadows and ridges located on the southeast portion of the caldera rim. Trees were located on the ridges and were a mix of mountain hemlock and whitebark pine. Many grasses, sedges, saplings, or fallen logs were present. The lowest elevation site, Pinnacles, was located on the southeast portion of the rim. This stand of trees was a mix of mature red fir and mountain hemlock with whitebark pine saplings.

Figure 3: Photographs of four of the mountain hemlock (*Tsuga mertensiana*) stands sampled in this study: (A) Lightning Springs (2,186 m), (B) Llao Rock (2,221 m), (C) Mount Scott (2,352 m), and (D) Palisade (2,050 m).

At each site, between 25 and 42 trees were sampled, with two cores recovered from each tree, yielding 228 trees in total. Cores were taken approximately 97 cm from the ground with a five-millimeter increment borer (Table 1). Trees had an average diameter at breast height of 95 cm. The largest tree sampled had a diameter of 195 cm and the smallest tree sampled was 54 cm.

Table 1: Metadata for mountain hemlock (*Tsuga mertensiana* [Bong.] Carr.) ring-width records collected in Crater Lake National Park.

Site	Site Code	Latitude (°N)	Longitude (°W)	Elevation (m)	Median DBH (cm)	Number of Trees	Number of Cores	Span of Record
Lightning Springs	LTS	42.93	-122.17	2,186	106.5	42	82	1449-2012
Llao Rock	LLR	42.97	-122.15	2,221	98.5	33	68	1566-2012
Pumice	PMP	42.98	-122.10	2,075	97.7	35	70	1490-2012
Palisade	PSD	42.97	-122.07	2,050	82.1	30	60	1474-2012
Mount Scott	MTS	42.93	-122.02	2,352	83.3	26	53	1508-2012
Castle Rock	CTR	42.92	-122.05	2,198	105.6	30	64	1510-2012
Pinnacle	PNC	42.91	-122.07	1,991	90.2	32	65	1569-2012

Laboratory Methods: Samples were mounted onto wooden core mounts and sanded according to standard dendrochronology procedures (Stokes and Smiley, 1968). Cores were crossdated using a combination of skeleton plotting and statistics, and total ring-width was measured using a Velmex measuring system to produce dated tree-ring width measurements (Stokes and Smiley, 1968; Cook and Kairiukstis, 1990; Speer, 2010). Finally, I used COFECHA software to check crossdating statistically (Holmes, 1983). Anatomical anomalies within rings were recorded, including frost rings (LaMarche and Hirschboeck, 1984) and light latewood bands (Tardif *et al.* 2011).

I used ARSTAN (Cook and Holmes, 1986) to estimate and remove biological growth trends including age, size, and stand dynamics in individual ring-width measurements (Fritts, 1971). Most commonly, ring-width records are standardized using linear regression or negative exponential curves (Fritts *et al.*, 1969). However, when tested the negative exponential curve only fit approximately twenty percent of samples and linear regressions (positive or negative) introduced bias. Therefore, I chose a smoothing spline (Cook and Peters, 1981) because they are data adaptive and provide closer agreement to the data. In order to select the best spline I used ARSTAN to test each ring-width series with a spline with a 50% frequency response of 50 years, then 100 years, and finally 200 years. After carefully examining the results of each of the seven records with each method, I chose to standardize my data with a cubic smoothing spline that preserved 50% of the total variance at a wavelength of 100% because the comparison noted no major differences between splines.

A correlation matrix was used to calculate the strength of the relationships between each of the seven chronologies over their common period. The expressed population signal (EPS), which determines the minimum series needed to reliably express the common signal (Wrigley *et al.*, 1984), was determined for each chronology. The r bar, the correlation between series within a site chronology (Wrigley *et al.*, 1984), was also computed for each record.

Climate Data: I obtained monthly climate data for CRLA from the United States Historical Climatology Network (USHCN). The USHCN is a network composed of 1,200 climate stations established in the mid-1980s to provide modern historical climate data that is both accurate and unbiased (Menne *et al.*, 2013; Quinlan *et al.* 1987). Sites for this program were selected using five criteria; (1) length of record, (2) the percentage of values that are missing, (3) spatial coverage, (4) the number of changes or moves made to the station that may affect data integrity, and (5) located rurally (Menne *et al.*, 2013). The USHCN filled in any missing data points from neighboring climate stations that were highly correlated with the CRLA station using a weighted average of values (Menne *et al.* 2013). Within the park, the station is located near the ranger's station at an elevation of 1,942 m on the southwestern portion of the caldera rim (Figure 1). Temperature and precipitation data for CRLA covers the period from A.D. 1893 to 2012, although some data points are missing prior to A.D. 1930.

Climate Analysis: I used SEASCORR (Meko *et al.*, 2011) to relate the annual growth pattern of the mountain hemlock chronologies to monthly precipitation (total) and temperature (mean) data from the park climate station. The program first calculates the monthly climate data into seasonal data then uses a Pearson correlation to compare it with a primary variable (precipitation) and then using a partial correlation to a secondary variable (temperature). Next, SEASCORR calculates the strength of the relationship between ring-width records and seasonal climate data and tests the significant of each association using a Monte Carlo simulation of the target tree-ring series (Meko *et al.*, 2011).

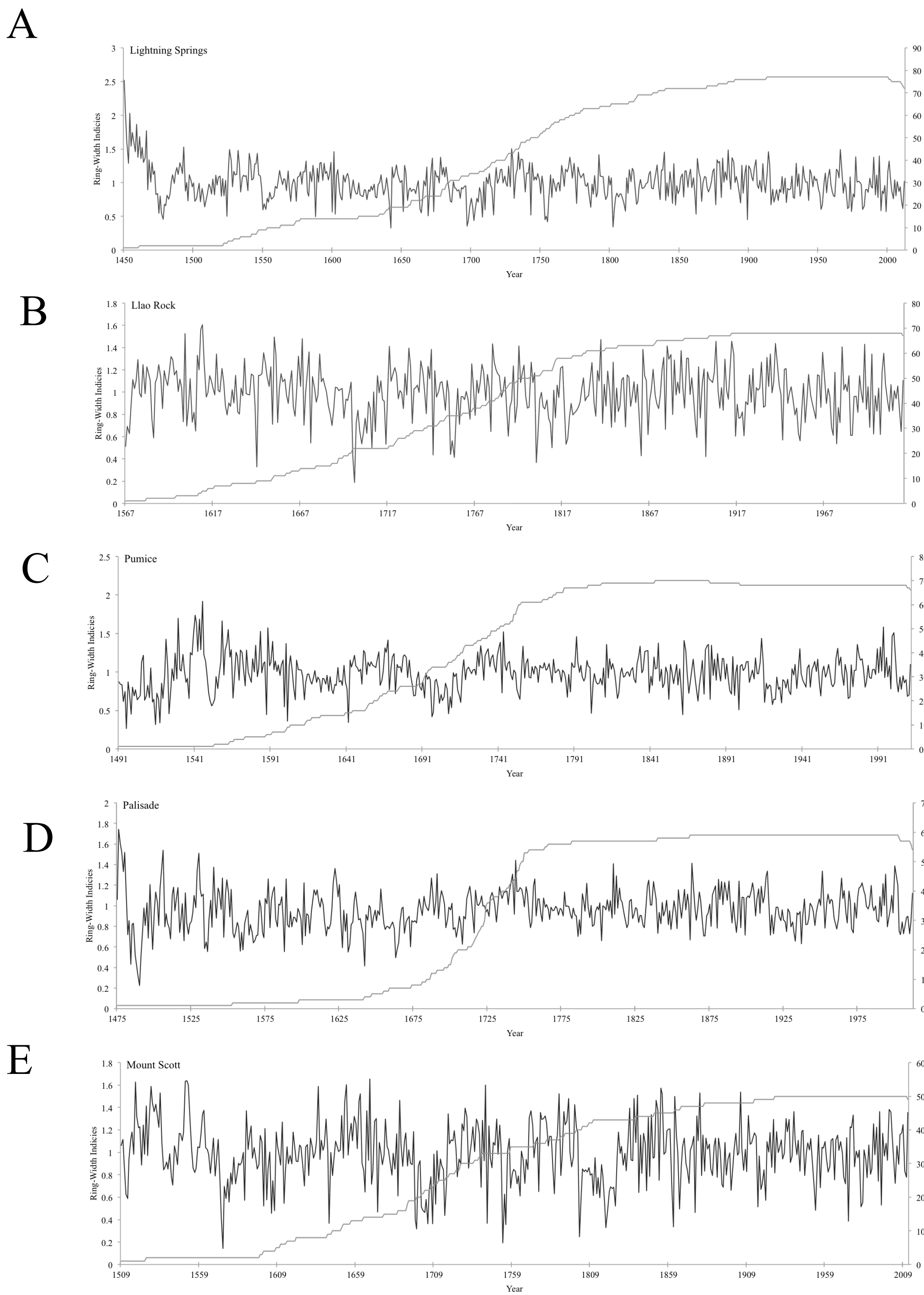
RESULTS

Ring-Width Measurements: I collected tree-ring specimens at seven locations around the rim of Crater Lake and produced tree-ring-width records that extend back 563 years into the 15th and 16th centuries. The mean segment lengths of each set range between 231 and 314 years, and average ring-width measurements vary from 0.784 to 1.181 mm per record (Table 2). Prominent (narrow) marker years (Speer, 2010) include A.D. 1573, 1587, 1599, 1601, 1641, 1672, 1715, 1742, 1754, 1785, 1801, 1810, 1876, 1899, and 1953.

Table 2: Metadata for seven standardized mountain hemlock (*Tsuga mertensiana*) chronologies collected in Crater Lake National Park.

Site	Mean ring width (mm)	Mean segment length (yr.)	r-bar	Last year when EPS >0.85
Lightning Springs	1.057	309	0.383	1540
Llao Rock	1.015	268	0.416	1644
Pumice	1.084	314	0.363	1578
Palisade	0.993	297	0.311	1701
Mount Scott	0.784	296	0.494	1645
Castle Rock	1.181	231	0.393	1712
Pinnacle	1.151	264	0.348	1706

Chronologies: Overall, the set of hemlock chronologies maintain a strong common signal (EPS > 0.85; Figure 4H) back to at least A.D. 1712 and as early as A.D. 1540. The between-tree correlation across the set is 0.31-0.49, which sits between the 30th and 70th percentile of all ring-width records in the Northern Hemisphere (St. George, 2014). The mean between-site correlation across all combinations of chronologies is 0.75 ($t<0.00001$, $p<0.01$; Table 3).


A
Lightning Springs
Ring-Width Indicies
Sample Depth
Year
B
Llao Rock
Ring-Width Indicies
Sample Depth
Year
C
Pumice
Ring-Width Indicies
Sample Depth
Year
D
Palisade
Ring-Width Indicies
Sample Depth
Year
E
Mount Scott
Ring-Width Indicies
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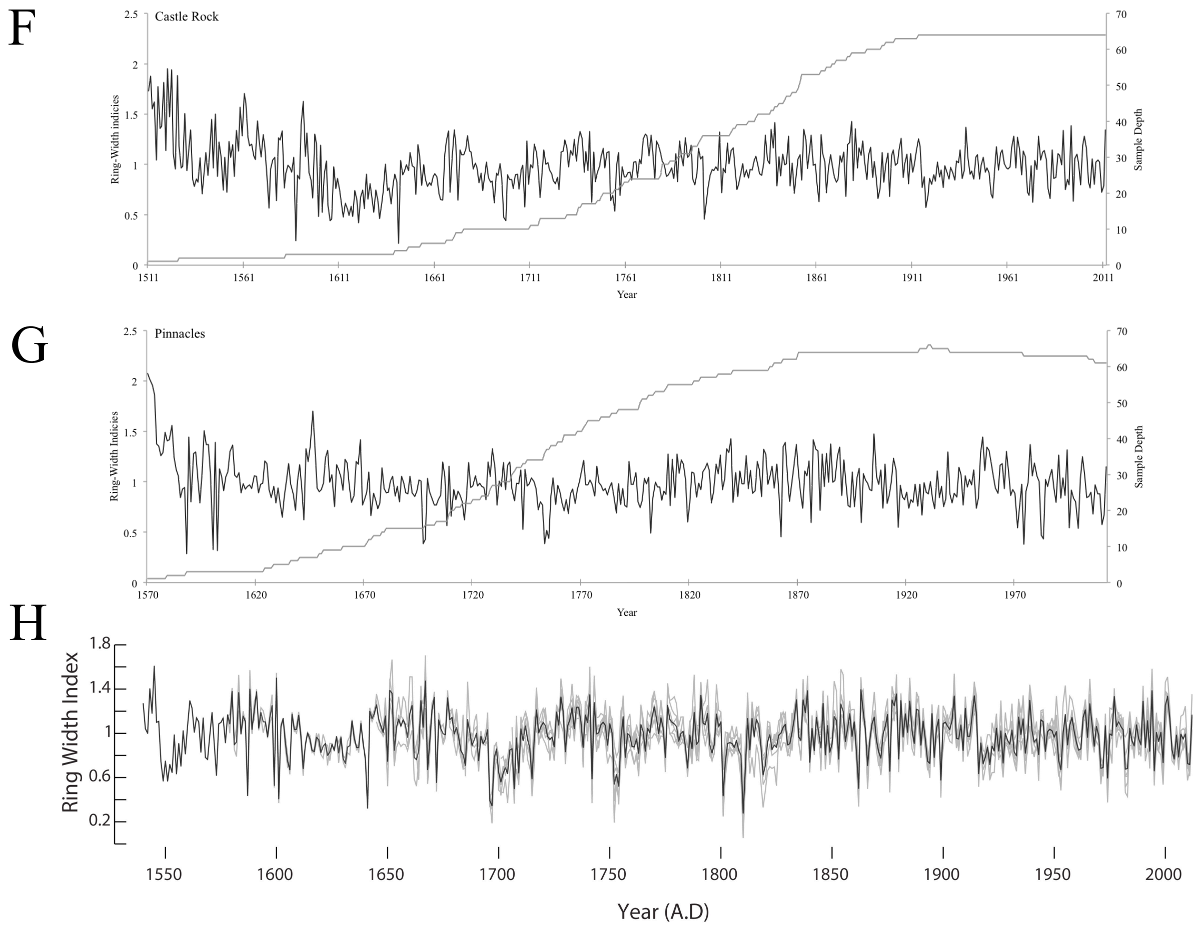

Figure 4: Tree-ring width chronologies and sample depth for (A) Lightning Springs, (B) Llao Rock, (C) Pumice, (D) Palisades, (E) Mount Scott, (F) Castle Rock, and (G) Pinnacles. The black lines represent the site chronology and the grey lines the sample depth (total number of cores) for each year. (H) Standardized tree-ring width chronologies for mountain hemlock sites in Crater Lake National Park. Grey lines represent chronologies for individual sites, while the black line shows the arithmetic mean of the entire set.

Table 3: Correlation matrix resulting correlation coefficients (r value) for the seven ring-width chronologies calculated over the records common period of A.D. 1712-2012.

	LLR	**PMP**	**PSD**	**MTS**	**CTR**	**PNC**	**Mean r**
LTS	0.93	0.82	0.65	0.76	0.85	0.83	0.80
LLR		0.78	0.57	0.84	0.83	0.78	0.76
PMP			0.83	0.67	0.78	0.76	0.76
PSD				0.51	0.67	0.63	0.60
MTS					0.79	0.69	0.74
CTR						0.78	0.78
PNC							

Anatomical Anomalies: Instances of anomalous tree growth were recorded and used to identify exceptional environmental conditions within the park prior to the twentieth century. Several types of anatomical anomalies were present in the mountain hemlock specimens, including locally absent rings, light latewood, and a feature I describe as 'traumatic lenses'. Locally-absent rings, or missing rings, occur when a tree forms a discontinuous layer of wood around the stem due to an environmental stressor (Schulman, 1941; Fritts *et al.*, 1965). Approximately 0.19 % of all mountain hemlock rings were absent, which is a relatively high fraction for trees outside of the American Southwest (St. George *et al.*, 2013). By far the most common missing ring across all seven sets was A.D. 1810, which was missing in 22% of the samples that cover that period. The highest percentage of A.D. 1810 missing rings occurred on the southwest portion of the caldera rim at Lightning Springs (missing in 45% of the samples spanning that year) and at the highest elevation site Mount Scott (41%). The sites with the lowest incident of the A.D. 1810 locally absent ring were Pinnacles, which had no instances of a locally absent ring in A.D. 1810, and Palisade (1.5%). The second-most common locally-absent ring occurred in A.D. 2010, which was missing in approximately two percent of series covering that year.

I also observed instances where hemlock rings include anatomical features that resemble traumatic resin ducts, which form as a response to physical injury or environmental stress (Hoadley, 1990). However, compared to typical examples of traumatic resin ducts (Nagy *et al.*, 2000; Luchi *et* al., 2004), these features are much larger, have a lens-like shape (instead of being circular), and are sometimes associated with frost damage. Therefore, while these features appear to be products of some type of trauma, it is not appropriate to identify them as traumatic resin ducts or frost rings. To our knowledge, these features have not been previously observed in mountain hemlock (Wiles, personal communication; Krusic, personal communication) and should be studied further, including formal anatomical description based on thin sections. These features are most prominent in A.D. 1809, and appear in 20% of specimens that span that year. These traumatic lenses are present in 28% from Lightning Springs, 25% from Llao Rock, 16% from Pumice, 3% from Palisade, 12% from Mount Scott, 8% from Castle Rock, and 2% from Pinnacles.

Light latewood bands are characterized by incompletely formed latewood cells and are frequently light in color due to partial cell wall formation (Tardif *et al.*, 2011). Light latewood bands were common and synchronous across the records and were useful as marker rings to crossdate ring-width series. Years with light latewood common across sites (0.97% of rings had a light latewood band) include A.D. 1601 (seen in 43% of samples covering that year), 1612 (27%), 1754 (18%), 1801 (23%), 1809 (41%), 1837 (10%), 1862 (22%), 1881 (10%), 1884 (10%), 1893 (47%), and 1927 (15%).

The final structure observed was frost rings, which occur when extracellular water freezes causing dehydration and the collapse of the outermost zone of affected cells (LaMarche and Hirschboeck, 1984). Throughout the records frost rings showed very little synchrony across the seven sites. Frost rings appeared in approximately 0.91 percent of all rings.

Tree Growth Response of Mountain Hemlock to Seasonal Climate: Our analysis of mountain hemlock in CRLA shows an inverse relationship between growth and cool season precipitation and a significant but more modest positive relationship between growth and growing season temperature. When comparing climate data and tree-ring-width records for each month, most chronologies show a significant inverse correlation between tree-ring-width and total precipitation during the previous November, previous December, and January, March and April of the current growth year (Figure 5a). For individual months, mountain hemlock growth is most strongly correlated with total precipitation in December prior to the growth year (Figure 5a). February shows no significant correlations between tree-ring-width and precipitation. Pumice and Palisades, and to a lesser extent Castle Rock, do not show as strong of signals. A partial positive correlation between growth and temperature is also noted primarily with the month of May and to a lesser extent April-August and the previous November and December.

When the analysis was repeated using three-month totals and averages, our results indicate that mountain hemlock growth is inversely correlated with cool-season precipitation (previous November-May; Figure 5b). The upper range of the relationship with three-month precipitation is exceptionally strong compared to other Northern Hemisphere records exhibiting that style of association (St. George, 2014). More evidence for the positive relationship with previous August precipitation is seen when the three-month total precipitation is correlated with tree growth. Over a three-month window, Castle Rock shows the same signal as Lightning Springs, Llao Rock, Mount Scott, and Pinnacles, but Pumice and Palisade still do not show the same response. With three-month totals, mountain hemlock growth is enhanced by previous November and previous December and growing season temperature (April-August), but the relationship with temperature is not as strong as with cool season precipitation.

Pumice and Palisades appear to show a slightly different climate signal compared to the other five sites. Pumice shows a negative correlation with December of the previous year precipitation and a positive partial correlation with temperature during the same month and May of the current year. Palisade shows a positive correlation with precipitation during August of the previous year and a negative relationship with temperature of the same month.

Precipitation (one-month total)

	pAug	pSep	pOct	pNov	pDec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
LTS	0.19			-0.23	-0.34	-0.25		-0.28	-0.24				-0.18	
LLR				-0.31	-0.42	-0.29		-0.29	-0.24				-0.22	
PMP				-0.20										
PSD	0.23													
MTS				-0.25	-0.34	-0.28		-0.24						
CTR	0.22				-0.23									
PNC				-0.26	-0.28	-0.24								

Temperature (one-month mean)

	pAug	pSep	pOct	pNov	pDec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
LTS	-0.25			0.25	0.25				0.25	0.31				
LLR	-0.19			0.27	0.22				0.24	0.29	0.22	0.24	0.28	
PMP	-0.22				0.30					0.25				
PSD	-0.22													
MTS				0.34	0.17					0.26		0.21	0.21	
CTR	-0.23			0.20	0.31					0.20				
PNC	-0.27			0.19	0.31					0.23				

Figure 5a: Correlation coefficients describing the association between mountain hemlock and monthly climate data from the United States historical Climate Network station within Crater Lake National Park. Positive (inverse) correlations are represented by red (blue) shading and dark (light) shading marks correlation coefficients that are significant at the 0.01 (0.05) level. Site names in the left column are abbreviated as follows Lightning Springs (LTS), Llao Rock (LLR), Pumice (PMP), Palisade (PSD), Mount Scott (MTS), Castle Rock (CTR), and Pinnacle (PNC).

Precipitation (three-month total)

	pAug	pSep	pOct	pNov	pDec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
LTS	0.22			-0.24	-0.38	-0.41	-0.42	-0.36	-0.35	-0.34	-0.19			
LLR				-0.30	-0.47	-0.50	-0.47	-0.38	-0.34	-0.34	-0.20			
PMP	0.31						-0.21							
PSD	0.30	0.20	0.21							-0.23				
MTS				-0.27	-0.37	-0.43	-0.41	-0.34	-0.27	-0.25				
CTR	0.27	0.18			-0.25	-0.28	-0.29	-0.24	-0.22	-0.18				
PNC	0.21			-0.23	-0.33	-0.38	-0.35	-0.29	-0.25	-0.23				

Temperature (three-month mean)

	pAug	pSep	pOct	pNov	pDec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
LTS	-0.38	-0.35			0.29	0.27			0.22	0.31	0.35	0.31	0.24	
LLR	-0.29	-0.28			0.29	0.29				0.30	0.37	0.38	0.36	0.23
PMP	-0.40	-0.24			0.27	0.27	0.20				0.24			
PSD	-0.46	-0.37												
MTS	-0.30	-0.22			0.24	0.27					0.27	0.33	0.30	0.22
CTR	-0.37	-0.32			0.29	0.29								
PNC	-0.37	-0.26			0.30	0.27	0.18			0.21	0.26	0.25		

Figure 5b: Correlation coefficients describing the association between mountain hemlock and seasonal climate data from the United States historical Climate Network station within Crater Lake National Park. Positive (inverse) correlations are represented by red (blue) shading and dark (light) shading marks correlation coefficients that are significant at the 0.01 (0.05) level. Site names in the left column are abbreviated as follows Lightning Springs (LTS), Llao Rock (LLR), Pumice (PMP), Palisade (PSD), Mount Scott (MTS), Castle Rock (CTR), and Pinnacle (PNC).

DISCUSSION

Tree Growth Response to Climate: Our new network of tree-ring-width records from CRLA demonstrates that the radial growth of mountain hemlock has been highly synchronous over the last five centuries (Figure 4). Strong agreement between the set of seven chronologies likely reflects the fact that hemlock growth at these locations are mostly regulated by the same environmental factors. There is no evidence of strong decadal variability after A.D. 1930 in either mountain hemlock or local climate data (Figure 2 and 4), which provides further evidence that the vigorous 14-15 year pattern in winter precipitation across the central Pacific Coast (Ault and St. George, 2010; St. George and Ault, 2011) is largely absent from CRLA.

After comparing annual records of mountain hemlock tree-ring-width against local monthly climate data, I found that, at these high-elevation sites, growth of this species is most strongly influenced by total cool-season (previous November, previous December, and January, March and April) precipitation. The association between mountain hemlock growth and cool-season precipitation is consistently and strongly inverse, with narrow rings formed during the growing season following deep and persistent snow packs. This result matches the overall climate response exhibited by mountain hemlock at sites across the Pacific Northwest, which is believed to be caused by lower soil temperature which delays the start and thus decreases the overall length of the growing season (Graumlich and Brubaker, 1986; Peterson *et al.*, 1999; Peterson and Peterson, 2001). The association between hemlock growth and winter precipitation is similar to other reports (Graumlich and Brubaker, 1986; Peterson *et al.*, 1999; Peterson and Peterson, 2001), which is consistent with the broader geographic pattern exhibited by the species (Gedalof and Smith, 2001; Peterson and Peterson, 2001). Although many tree-ring width records from western North America are strongly influenced by winter precipitation, this type of ‘reversed’ association (where more moisture leads to suppressed tree growth) is largely restricted to sites in the Pacific Northwest (St. George, 2014). Crater Lake is one of the southernmost locations in North America where tree-ring width records display this type of inverse relationship (St. George, 2014).

Previous mountain hemlock records from CRLA also show the same inverse relationship with cool-season precipitation (Peterson *et al.*, 1999; Peterson and Peterson, 2001). Further north in the Cascade Range of Washington state, mountain hemlock records show an inverse relationship with March snowpack (Graumlich and Brubaker, 1986), which is consistent with my results. This relationship is supported again further north in the Coast Range of British Columbia, Canada, where Hart *et al.* (2010) showed an inverse relationship with April first snow-water equivalent, the conversion of existing snowpack into the amount of water it would equal based on the area and density of the snow.

Additionally, tree-ring-width records of mountain hemlock were partially correlated with monthly climate data, and I found that tree growth is influenced by May and, to a lesser extent, April-August and previous November and December temperature. The observed relationship between mountain hemlock and temperatures is strong compared with other reports from Oregon, such as Peterson and Peterson (2001), which reported a relationship with April-May temperature ($r = 0.09$). However, across the entire range of the species, growing season temperature has the strongest correlation with hemlock in the Gulf of Alaska (Gedalof and Smith, 2001; Peterson and Peterson, 2001). These results are also consistent with broader climate relationship trends described across the range of mountain hemlock. At the highest latitude sites, temperature is the primary limiting factor; however, at lower latitudes winter precipitation becomes the deciding factor (Gedalof and Smith, 2001; Peterson and Peterson, 2001).

500-Year History: Mountain hemlock records at high-elevation sites in CRLA are strongly and significantly correlated with total (November-May) precipitation (and, to a lesser degree, late spring temperatures); we suggest these data may be interpreted as a surrogate measure of cool-season precipitation across the park. Under this interpretation, low growth intervals are the primary result of a large amount of winter precipitation and partially due to cooler summer temperatures, which resulted in shorter growing seasons. High growth periods, conversely, are primarily the result of low snow levels in the winter and partially due to warmer summer temperatures leading to longer growing seasons.

The chronologies show variability of 30-50 years that dampens out around A.D. 1930 (Figure 4). The most notable decade of high snowpack was from A.D. 1801-1810, which includes two key marker rings, A.D. 1801 and 1810, with 1810 being the narrowest ring across all seven records (Table 4). Two additional intervals of persistently high snow and/or cool summers appear to have occurred between A.D. 1695-1707 and 1750-1755. Low-snow intervals include A.D. 1543-1547, 1651-1653, 1877-1879, 1913-1915, and 2000-2002. The warm interval A.D. 1543-1547 includes 1545 and 1543, which are the widest ring and the fourth-widest ring respectively.

Table 4: Ten lowest and highest years of *Tsuga mertensiana* growth, as represented by the mean ring-width index of all seven chronologies.

Top 10 low growth years		**Top 10 high growth years**	
Year	**Ring-width-indices**	**Year**	**Ring-width-indices**
1810	0.28	1545	1.61
1641	0.32	1600	1.50
1697	0.35	1667	1.47
1696	0.39	1543	1.40
1601	0.41	1588	1.40
1801	0.44	1863	1.39
1587	0.44	1651	1.39
1707	0.50	1839	1.38
1862	0.50	1994	1.38
1754	0.52	1580	1.38

Other tree-ring records within the park (Briffa *et al.*, 1992; Peterson *et al.*, 1999; Briffa *et al.*, 2002) support these apparent cool/wet intervals within the chronologies, including A.D. 1695-1707, 1750-1755, and 1801-1810. Likewise, the warm intervals of A.D. 1651-1653 and 1877-1879 have also been previously described (Briffa *et al.*, 1992; Briffa *et al.*, 2002). Additional tree-ring studies in the region include a reconstruction of the hydroclimate of the Upper Klamath basin by Malevich *et al*. (2013), a reconstruction of the Sacramento River by Meko *et al*. (2001), and a reconstruction of the precipitation in the Pacific Northwest by Graumlich (1987). Malevich *et al*. (2013) used data from the International Tree-Ring databank from western juniper (*Juniperus occidentalis* Hook.), ponderosa pine (*Pinus ponderosa* Dougl. ex Laws), Jeffery pine (*Pinus jeffreyi* Grev. & Balf.), and blue oak (*Quercus douglasii* Hook. & Arn.) to reconstruct the hydroclimate of the Upper Klamath basin. Their study highlights evidence of drought conditions in periods earlier than the CLNP records presented here. However, they report A.D. 1729 as a drought year (Malevich *et al*., 2013), which my records suggest is a period of high growth, or the early melt of snowpack and an extended growing season. Meko *et al*. (2001) selected 36 tree-ring sites of a variety of species in southern Oregon and northern California to build a reconstruction of the flow of the Sacramento River. The top ten discharge years all coincide with high or moderate growth at Crater Lake. A reconstruction of precipitation across the Pacific Northwest was built from 41 sites of drought sensitive trees throughout Washington, Oregon and northern California, and is composed of a variety of species (Graumlich, 1987). This study breaks the Pacific Northwest into three regions: the Western Lowlands, the Columbia Basin, and the Southern Valleys (including CRLA). The author reports the top twenty drought years for each region and the Southern Valley's dates are A.D. 1889, 1967, 1721, 1739, 1959, 1717, 1909, 1929, 1961, 1839, 1856, 1973, 1924, 1931, 1683, 1920, 1918, 1822, 1880, and 1675 (Graumlich, 1987). My records reliably express the common signal to A.D. 1712 so I cannot make comparisons before that period. However, my records show high to moderate growth during a majority of these years. However, three exceptions are A.D. 1880, 1909, and 1918, which my records show are moderate a low growth years.

I also examined paleolimnological records from three central Oregon lakes and a pond (Summer Lake, Fish Lake, Upper Klamath Lake, and Diamond Pond; Verosub *et al.*, 1986; Wigand, 1987; Cohen *et al.*, 2000; Negrini *et al.*, 2000; Reynolds *et al.*, 2004; Rosenbaum and Reynolds, 2004), which are located within 300 km of CRLA, and two speleothem records from the Oregon Caves National Monument (Vacco *et al.*, 2005;

Rushdi *et al.*, 2011) which are located approximately 150 km southwest of CRLA in the Klamath Mountains to test for overlap with my annual ring-width series. All but one record did not have a high enough resolution reported over the period covered by this data to determine whether they illustrated a similar pattern. However, Wigand (1987) reports on the findings at Diamond Pond, spanning 6,200 years and writes that a pollen record obtained from this pond shows a local increase in grasses and juniper at 300 B.P. (~A.D. 1650), which the author infers is an indication of wetter conditions. However, my data at this time show the beginning of a high growth interval, which I suggest is evidence of lowered winter precipitation.

1809/1810: During the five centuries covered by the Crater Lake mountain hemlock record, the period between A.D. 1809 and 1811 stands out because of its exceptionally low tree growth and its high frequency of anatomical anomalies. Mountain hemlock growth reached its lowest point in A.D. 1810 and the 1810 ring is the most frequently absent (missing in 22% of samples covering that year). The A.D. 1809 ring is of average width, contains traumatic lenses (20% of samples), and terminates with a light latewood band (41% of samples). Next, A.D. 1810 follows as either a locally absent ring or a narrow ring (Figure 6a and 6b). The A.D. 1811 ring is a moderately narrow ring and the 1812 ring is wide.

I suggest these features may be evidence of a sequence of unique events that affected CRLA, starting at the end of the A.D. 1809 growing season. Under this scenario, the frequent light-latewood bands (Figure 6c) would be the product of an abrupt shutdown of cambial activity due to unseasonably cold temperatures, as the formation of light latewood bands in alpine environments is often triggered by below-average temperatures during the summer or fall or an overall shorter season (Filion *et al.*, 1986; Gindle, 1999; Tardif *et al.*, 2011). The cause of the high numbers of traumatic lenses (Figure 6e) is unknown but suggests some kind of widespread trauma. High snowfall through the winter of 1809-1810 and cool temperatures permitted snow to persist well into the growing season. Records of April first snow water equivalent in (A.D. 1940 to present; United States Department of Agriculture, 2014) show that missing rings most commonly form after high snowpack winters (Figure 7), which suggests that the high frequency of locally absent rings or very narrow rings that formed in A.D. 1810 could have been caused by a much shortened growing season (Figure 6d and 6e). Across the park, hemlock growth remained somewhat low in A.D. 1811, which implies weather conditions were either still cool or that trees were continuing to recover from the earlier environmental shock. Finally, A.D. 1812 is a wide ring suggesting a longer growing season and tree recovery. This event coincides with the unknown stratospheric eruption that is thought to have occurred in the winter of A.D. 1808-1809 (Cole-Dai *et al.*, 2009; D'Arrigo *et al*., 2009), and although we do not imply that this sequence of abnormal rings is a direct consequence of that eruption, they may be a local expression of the regional climate response to that forcing.

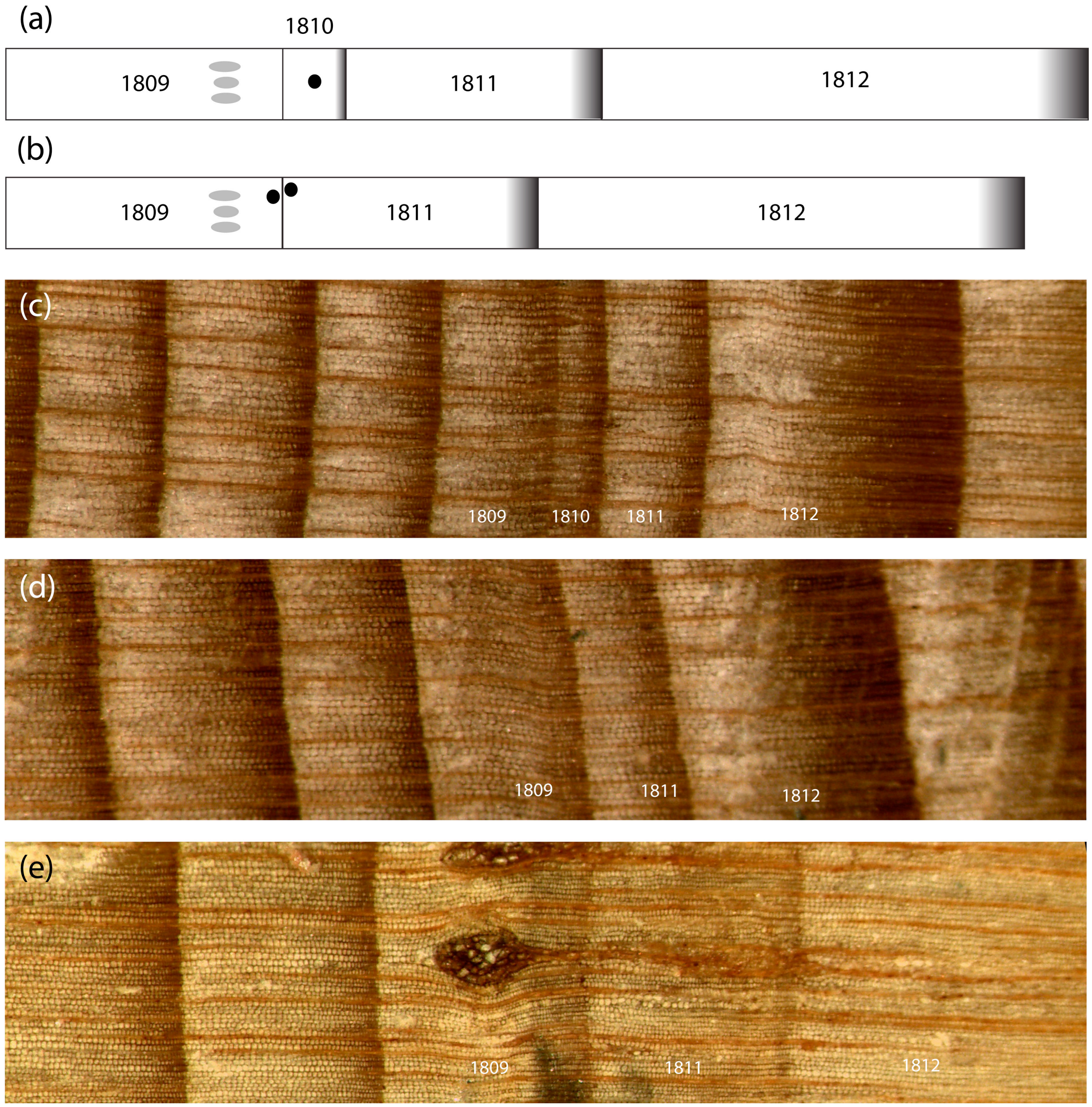

Figure 6: Feature of mountain hemlock (*Tsuga mertensiana*) growth during the A.D. 1809/1810 episode. (a and b) schematic diagrams illustrating the typical sequence in mountain hemlock specimens. Gray ovals represent traumatic lenses, thin line indicates light latewood, and offset diagonal circles mark locally absent rings. Photographs of specimens exhibiting (c) light latewood band in A.D. 1809, (d) light latewood in A.D. 1809 and a missing ring in 1810, and (e) traumatic lenses in 1809 and a locally absent ring in A.D. 1810.

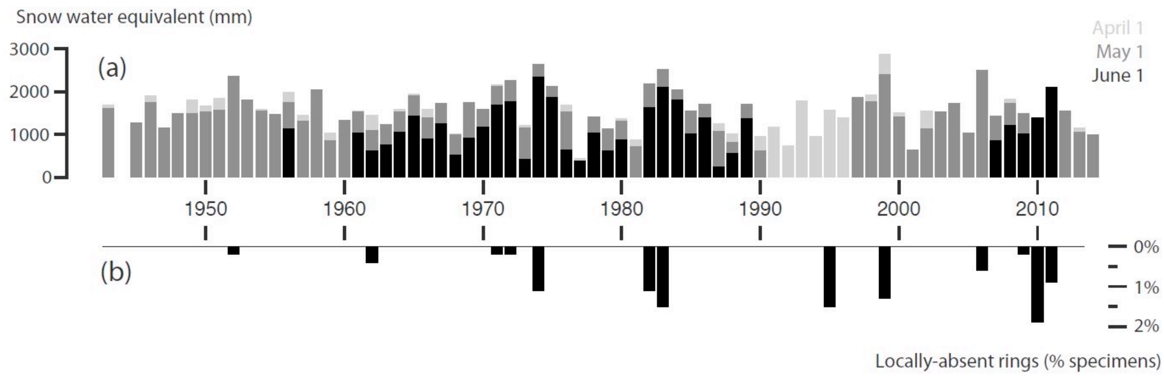

Figure 7: Snow water equivalent data (United States Department of Agriculture, 2014) from Crater Lake National Park. (a) Annual snow water equivalent from A.D. 1940-2012 with available totals for April first (light gray), May first (medium gray), and June first (black). (b) Percentages of locally absent rings from A.D. 1940-2012.

Implications to park management: This network of seven ring width records will inform park managers about past climate, mountain hemlock growth, and potentially park hydrology. Trees recorded several instances of winters with conditions that led to a shorter growing season. High elevation hemlock in Crater Lake showed higher growth rates in relationship with longer growing seasons possibly caused by warmer winters, an early and warm spring, or low snow. Additionally, this species showed no change in growth over time in spite of recent decline reported in spring snowpack in the northern Cascade Mountains (Stoelinga *et al.,* 2010). Finally, though outside the scope and timeline of this project, these ring-width series could be used as part of a reconstruction of surface hydrology back approximately 300 years.

CONCLUSION

My new set of tree-ring-width records from high-elevation sites in CRLA, Oregon showed that the radial growth of mountain hemlock trees has been highly synchronous over the last five centuries. This pattern suggests tree growth across the Park has been largely controlled by the same set of environmental factors during that interval. Comparing my tree-ring width records against modern monthly climate data from the United States Historical Climate Network, I determined that cool-season precipitation is the dominant influence on tree growth in this region, with summer temperature having a significant, but secondary, effect. The inverse association between cool-season precipitation and hemlock growth is opposite to the relationship displayed by most tree-ring records in western North America. Prior research has shown that deep, persistent snowpack reduces the growth of mountain hemlock, and because Crater Lake is near the southern limit of this species' range, this influence is particularly strong. Based on the observed association between hemlock growth and climate, I identified several periods during the past five centuries where snowpack in CRLA was persistently high or low. The hemlock network contains abundant anatomical evidence of unusual growth throughout the record, but A.D. 1809-1811 stands out as the most anomalous. I interpret the anatomical evidence for this event as the early onset of winter in A.D. 1809, an exceptionally short growing season in A.D. 1810, and either continually cool weather conditions or recovery from the earlier environmental shock in A.D. 1811. This new proxy record extends our knowledge of climate patterns and extremes near CRLA back five centuries and shows that cool-season precipitation in the central Pacific Coast has varied over time, and the region experienced several extreme events unlike anything that occurred during the instrumental period.

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